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Viscous dissipative forced convection in thermal non-equilibrium nanofluid-saturated porous media embedded in microchannels ☆

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ABSTRACT

Under local thermal non-equilibrium and isoflux boundary conditions, the two-energy-equation model is employed to investigate the effect of viscous dissipation on the thermal characteristics of nanofluid flow through a porous medium embedded in a microchannel. Analytical closed-form solutions of the two-dimensional temperature distributions are obtained for the models with and without the viscous dissipation terms in the energy equation. The analysis emphasizes on the disparities induced by the viscous dissipation between the two models. The use of porous medium is capable to enhance the thermal performance up to 53%. When the viscous dissipation effect is neglected, the thermal performance of nanofluid is overrated as much as 60%, sufficiently serious to trigger an attention in the performance analysis. The heat transfer coefficient of nanofluid is found to be enhanced in the low-Reynolds-number flow regime but it declines in the high-Reynolds-number flow regime. By reducing the size of nanoparticle, the thermal performance can be enhanced as much as 70%. Furthermore, the thermal performance can be further augmented by increasing the channel aspect ratio as well as by increasing the thermal conductivity of the porous material. This study serves as a useful analytical tool for the design and performance characterization of an integrated system incorporating the use of nanofluid and porous medium into a microchannel.

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1. Introduction

The miniaturization of microelectronic devices poses a challenging thermal management problem. The shrinking in the size of the microelectronic components has led to the elevated power dissipation per unit chip area. To improve the cooling performance of miniaturized devices, microchannel heat sink is deemed to be one of the promising solutions in light of its high heat removal rates. The choice of working fluid is of vital importance in enhancing the thermal performance of this cooling device. The low thermal conductivity of the conventional fluid poses a primary limitation to the development of high-performance heat-transfer fluid. The suspension of the ultra-fine nanoparticle in the conventional fluid can prominently increases the effective thermal conductivity of fluid even with a small volume fraction of nanoparticle. This kind of fluid was coined "nanofluid" [1]. Nanofluids show great potential in enhancing the heat transfer performance of the flow [2–4]. Numerous theoretical studies have been performed to investigate various effects related to hydrodynamic and thermal characteristics of nanofluids [5–11]. For forced convection in macro-scale channels, it is a common practice to neglect the effect of viscous dissipation. However, such effect is considerably significant in microchannel due to its large length-to-diameter ratio, leading to drastic changes in the flow and temperature fields of the fluid [12]. Viscous dissipation features a heat source in the fluid flow, inducing an appreciable rise in fluid temperature due to the conversion of kinetic motion to thermal energy. The viscous dissipation effect is appreciably significant in the fluid flow passage of hydraulic diameter less than 100 μm [13]. The effect of viscous dissipation is further enhanced in fluids of low specific heat and high viscosity, such as nanofluids of which the specific heat is reduced and the viscosity is increased due to the suspension of solid nanoparticle in the fluid [12]. It has been shown that the thermal performance of microchannel is overrated when the viscous dissipation is neglected [5]. Concurrently, it has also been pointed out that the suspension of nanoparticle in fluid intensifies the viscous dissipation effect [14]. Judging from this, the viscous dissipation effect plays a crucial role in the heat transfer characteristics of forced convection of nanofluid flow in microchannels.

Innovative methods have been devised to improve the thermal performance of heat sinks. It has been reported that by embedding porous media into microchannels, the surface contact area-to-volume ratio of the flow can be enhanced [15,16]. The use of porous media has been widely acknowledged for enhancing heat transfer with an accompanying rise of pressure drop in the flow passage. The local velocity mixing of the working fluid is increased, leading to higher heat transfer coefficient [17]. The thermal performance of a microporous heat exchanger is higher than that of a conventional microchannel [18]. Therefore, the embedment of porous media in microchannel is a promising high-heat-flux removal method in the

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Nomenclature

a_i	specific surface area (m^{-1})
Bi	Biot number
Br′	modified Brinkman number
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
D	hydraulic diameter of microchannel (m)
Da	Darcy number
d_p	diameter of nanoparticle (m)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_i	interstitial heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	half-height of the microchannel (m)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
K	permeability (m^2)
Kn	Knudsen number
L	length of the microchannel (m)
M	viscosity ratio as defined in Eq. (8)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux ($W\ m^{-2}$)
Re	Reynolds number
S	shape factor of the porous medium
T	temperature (K)
$\overline{T}$	bulk mean temperature (K)
u	nanofluid velocity ($m\ s^{-1}$)
$\overline{u}$	cross-sectional averaged nanofluid velocity ($m\ s^{-1}$)
U	dimensionless nanofluid velocity
$\overline{U}$	cross-sectional averaged dimensionless nanofluid velocity
x	longitudinal coordinate (m)
X	dimensionless longitudinal coordinate
y	transverse coordinate (m)
Y	dimensionless transverse coordinate

Greek symbols

ϕ	nanoparticle volume fraction
θ	dimensionless temperature
κ	effective thermal conductivity ratio as defined in Eq. (23)
μ	dynamic viscosity ($N\ s\ m^{-2}$)
ρ	density ($kg\ m^{-3}$)
λ	molecular mean free path (m)
ξ	aspect ratio of the microchannel
ε	porosity of the porous medium

Subscripts

eff	of porous medium effective properties
f	of base fluid
fh	of frictional heat generation
ih	of internal heat generation
in	value at the channel entrance
nf	of nanofluid
p	of nanoparticle
s	of porous medium solid phase
vd	of viscous dissipation
w	of channel wall
1	of Model 1
2	of Model 2

miniaturized devices. Arising from the frictional heating due to the increasing contact of the fluid with the solid phase and the wall as well as the internal heating associated with the mechanical power needed to extrude the fluid through a porous medium, the effect of viscous dissipation of forced convection in porous media is absolutely indispensable [19–26].

Many studies of convection heat transfer in porous media are based on the local thermal equilibrium one-energy-equation model [19–23, 27,28]. However under certain circumstances, significant differences in the thermo-physical properties between fluid and solid phases in a porous medium induce a substantially large thermal resistance between the two phases. The difference in the temperature between the solid and the fluid phases arises and thus invalidates the assumption of local thermal equilibrium [29]. On the other hand, most studies adopting two-energy-equation model neglected the viscous dissipation effect [29–35]. In the up-to-date literature, there are only three studies employing two-equation model for forced-convection analysis in porous media by incorporating the viscous dissipation effect [24,25,36]. Parametric studies were performed to investigate the effect of viscous dissipation on the thermally developing and fully developed forced convection in porous-medium flow and it was reported that the one-equation-model significantly deviates from the two-equation model, and the Nusselt number is strongly dependent on the effect of viscous dissipation [24,25]. The convective heat transfer of the flow in porous media decreases with the presence of viscous dissipation [36].

The present study emphasizes analytical solutions for the temperature distributions and the Nusselt number of forced convection of nanofluid flow through porous media embedded in microchannels. Under local thermal non-equilibrium and isoflux boundary conditions, the two-energy-equation model is employed to investigate the forced convection in porous media by incorporating the viscous dissipation effect. As the viscous dissipation effect is unquestionably a requisite for forced convection of nanofluid flow in microchannels and porous media for individual case, needless to say, it would be futile to neglect such effect in the convection analysis of this integrated system. Up to date, none of the previous studies explicitly addresses the viscous dissipation effect on the heat transfer characteristics of nanofluid flow through porous media embedded in microchannels. Two-dimensional closed-form temperature distributions for both the solid and liquid phases are obtained. With the variations of various pertinent parameters such as nanoparticle volume fraction, nanoparticle diameter, Reynolds number and channel aspect ratio, the effect of viscous dissipation on the thermal performance is scrutinized. The underlying physical significance of the viscous dissipation in the forced convection of nanofluid flow through porous media embedded in microchannels is discussed. In addition, we identify the conditions for heat transfer enhancement and the analysis would be a useful analytical tool for the design and performance characterization of such integrated system.

2. Mathematical formulation

2.1. Thermophysical properties of nanofluid

In light of the suspensions of ultra-fine nanoparticles in base fluids, nanofluids exhibit distinctive thermophysical properties from conventional fluids. In the present study, water–Al_2O_3 nanofluid is selected as the working fluid. By taking into account the Brownian motion-induced convection from multiple nanoparticles, the effective thermal conductivity of water– Al_2O_3 nanofluid can be estimated as [37]

$$k_{nf} = C_k k_f, \tag{1}$$

where C_k is a constant coefficient defined as

$$C_k = \left(1 + A\mathrm{Re_b}^m\, \mathrm{Pr_f}^{1/3}\phi\right) \frac{\tau(1+2\alpha)+2+2\phi[\tau(1-\alpha)-1]}{\tau(1+2\alpha)+2-\phi[\tau(1-\alpha)-1]}. \tag{2}$$

The parameter $\tau = k_p/k_f$ is the thermal conductivity ratio of the particle thermal conductivity k_p to the base fluid thermal conductivity

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